

# Ionization of the atmosphere caused by solar protons and its influence on ozonosphere of the Earth during 1994–2003

Alexei Krivolutsky\*, Alexander Kuminov, Tat'yana Vyushkova

*Central Aerological Observatory, Department of Atmospheric Chemistry and Dynamics, Pervomayskaya Str. 3,  
Dolgoprudny, Moscow Region, Russian Federation*

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## Abstract

Satellite observations of solar proton fluxes in different energetic channels have been used to investigate proton activity of the Sun during 23rd cycle of its activity. Several maxima of solar proton intensity occurred in 1998, 2000, 2001, and in 2003, with a minima in 1999. Ionization of the atmosphere caused by several strongest solar proton events (SPEs) was calculated using energetic spectrums of solar protons. It was shown on the basis of the calculations that the revealed structure of ionization caused by different SPEs looks rather different from one SPE to another. The response of chemical composition (ozone and others) at 70°N to the strongest events was calculated using photochemical model. It was shown by photochemical calculations that ozone depletion in the stratosphere and mesosphere was strong not only after famous SPE in July 2000, but also after SPE in November 2001. Special focus was on SPEs that occurred during October–November 2003 period. The results of photochemical simulations has also shown that additional production of OH molecular by solar protons leads to water vapor increase in the middle atmosphere. Calculated increase equaled about 2% in the mesosphere after SPE in July 2000. At the same time, the last result needs additional investigations involving photochemical reactions with ions.

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**Keywords:** Solar protons; Ionization of atmosphere; Ozone change

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## 1. Introduction

The external influence on the ozone layer of the Earth is an important factor, when we are interested in the mechanisms of ozone variations on different time-scales. Solar energetic protons, are one among these factors. Some visible solar flares are accompanied by the emission of high-energy protons and also by electrons (and possibly, neutrons). Half an hour or more after the recording of a major visible flare, protons and heavier

nuclei with energies of up to 200 MeV, as well as electrons with energies of up to 100 MeV, are usually observed within the polar caps.

The energies of solar protons are usually bounded by fractions of giga-electron volt and sometimes reach several giga-electron volt. Its intensity decreases with increase in energy more steeply than that of galactic cosmic rays (GCRs) and the integral spectrum exponent varies between 2 and 7 from event to event (Lastovicka, 1989). The intensity of solar protons generated by a major, slowly growing flare increases for 30–32 h, while their rigidity decreases.

The intensity and number of major solar proton events are highly variable from one solar cycle to

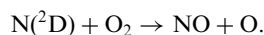
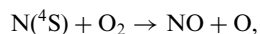
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\*Corresponding author. Tel.: +795 408 7945; fax: +795 576 3327.

E-mail address: [alkriv@netclub.ru](mailto:alkriv@netclub.ru) (A. Krivolutsky).

another. The absence of a direct correlation between the sunspot number and the frequency of solar proton events (SPEs) makes it difficult to reliably predict the intensity or frequency of SPEs. Observations indicate that the phenomena related to solar flares are more frequent at the maximum of solar activity. About ten events with particle energies of  $E > 1E + 7\text{ eV}$  per year are recorded near the solar activity maximum. No more than one such event can usually be observed in the years of minimum solar activity. However, although solar flares are less frequent at the solar activity minimum, their manifestations may be more dramatic, because the interplanetary magnetic fields pierced by flare particles have a simple structure and these particles reach the Earth more easily. In particular, one of the strongest SPE, in August 1972, occurred almost 3–4 years after the solar activity maximum (Fabian et al., 1979). The effect of a flare on the Earth's atmosphere depends on flux energy and spectrum rigidity. High-energy solar particles (with  $E > 30\text{ MeV}$ ) penetrate into the stratosphere, while lower energy protons affect the mesosphere.

Secondary electrons induced by solar protons during ionization of the atmosphere cause the dissociation or dissociative ionization of  $\text{N}_2$  producing atomic N in the following states:  $\text{N}^4\text{S}$  or  $\text{N}^2\text{D}$ . Then molecule of NO may be created in the reaction



At the same time molecule of NO may be destroyed in the following reaction:

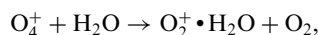


Finally, the production of NO depends on the produced amount of  $\text{N}^4\text{S}$  and  $\text{N}^2\text{D}$ . Theoretical calculations based on ionized and neutral chemistry gave the efficiencies of atomic nitrogen and oxygen production by relativistic protons impact in the atmosphere (Porter et al., 1976; Heaps, 1978; Jackman et al., 1979). It was found by the authors, that each pair of ions induced by protons in the atmosphere leads to the birth of 1.3 atoms of nitrogen and one atom of oxygen.

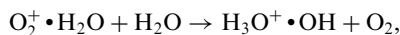
Additional amount of OH (Solomon et al., 1981; Solomon and Crutzen, 1981) may also be produced by energetic particles. For example, primary positive ions  $\text{O}_2^+$  react with molecular oxygen producing  $\text{O}_4^+$ :



which react with water vapor producing short-lived first hydrate component



which may produce molecules of OH by the following way



Full ion chemistry for D-region was described in several papers (see Heaps, 1978; Solomon et al., 1981). It was shown that each pair of ions gives approximately two molecules of OH in the mesosphere. Different authors gave different vertical distributions for additional OH production due to ionization by energetic protons (it depends also on ionization rates), but in general, such efficiency is reduced above 80 km and the efficiencies of OH production have a weak dependence on day to night variations (Solomon et al., 1981).

Additional molecules of NO and OH then change ozone and other minor species in the middle atmosphere. Chemical mechanisms described above were intensively used in photochemical computations to estimate ozone response caused by energetic protons during solar cycles, including major SPEs like those which occurred in August 1972, October 1989, etc. (Jackman et al., 1980, 1996; Jackman and McPeters, 1985; Vitt and Jackman, 1996). Calculated response of neutral species and electron density to SPE in October 1989 showed strong increase of electron density (Krivolutsky et al., 2001b) after SPE. SPE of July 2000 (Bastille Day event) was studied by photochemical modeling and UARS data analysis (Jackman et al., 2000, 2001; Krivolutsky, 2001a; Quack et al., 2001). These studies showed that ozone in the mesosphere was strongly destroyed (about 70–80%) after this event. Quantitative correspondence was found in ozone changes between model simulations and data analysis (UARS, HALOE—Jackman et al., 2001; Krivolutsky, 2001a; NOAA 14, SBUV/2—Jackman et al., 2001). At the same time, observations of  $\text{NO}_x$  by HALOE instrument showed smaller  $\text{NO}_x$  response than in calculations (Jackman et al., 2001). So, we may conclude that there exists good correspondence between ozone changes in the model runs and observations caused by increased  $\text{HO}_x$  in the mesosphere.

The results of rocket measurements of the middle-atmosphere parameters performed at mid-latitudes of the Southern Hemisphere during SPE of October 1989 (Zadorozhny et al., 1992, 1994) showed a strong increase in of ion number density above 30 km and of nitric oxide concentration above 40 km with maxima of  $2E + 9$  molecules per cubic centimeter at 45–55 km. The ozone concentration after SPE above 35 km was reduced (maxima of depletion was around 20–25% at 50 km). Temperature decrease between 40 and 60 km was also found in rocket experiment (about 14 K near 50 km). These measurements are qualitatively agreed with photochemical conceptions of SPEs influence on the

middle atmosphere. However, it was found that cooling in the stratopause was stronger than predicted theoretically.

Relativistic electrons may also influence the chemical composition of the atmosphere (Thorne, 1977; Callis, 1997; Aikin and Smith, 2000).

In this paper we present results which demonstrate proton activity of the Sun during 23rd solar cycle, a structure of ionization rates for selected (the most pronounced) SPEs, including those that occurred in October 2003, and the response of ozonosphere (photochemical simulations) caused by these events.

## 2. Proton activity of the sun during 1994–2003

Information about proton fluxes (fluences) based on the measurements from the boards of GOES satellites (<http://spidr.ngdc.noaa.gov/spidr/>) was used for analysis. Daily mean sums of total energy for proton flux in the range 1–100 MeV for third integral energetic channels ( $>1$ ,  $>10$ , and  $>100$  MeV) have been calculated to have a general picture of solar proton activity. Fig. 1(a) shows temporal characteristic of proton activity during last decade (1994–2003). The presented figure illustrates well the minima of solar

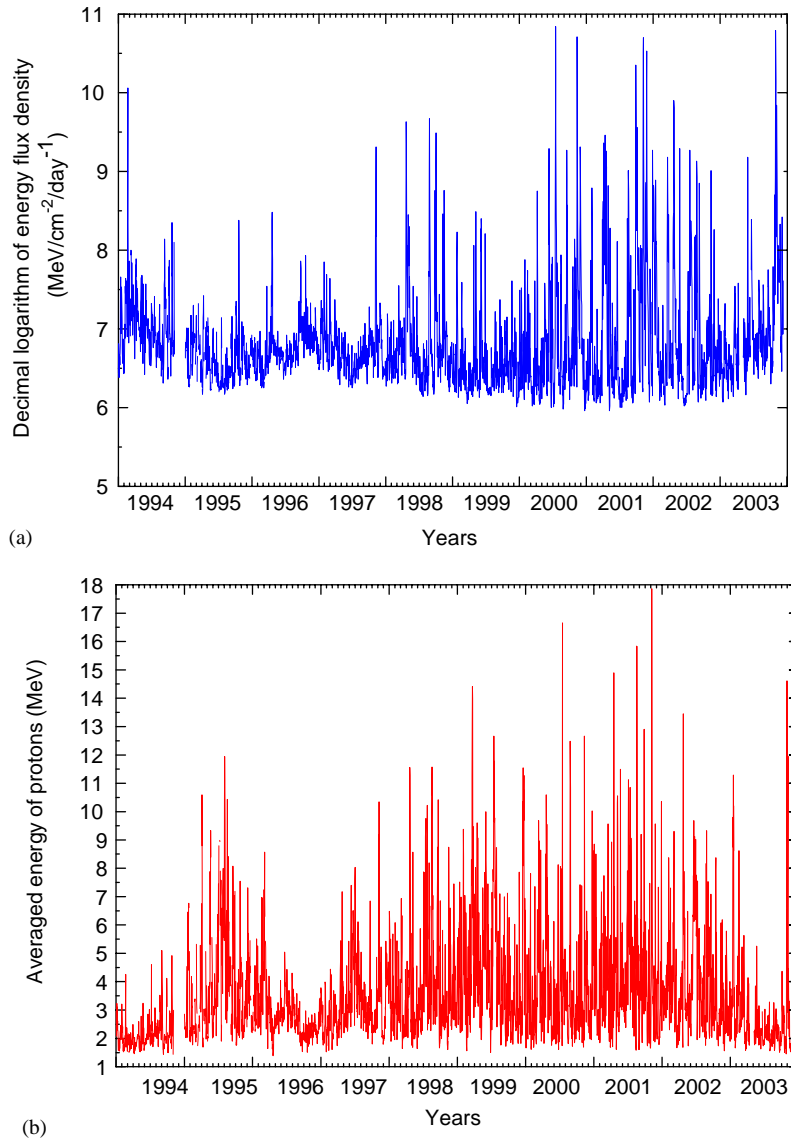


Fig. 1. (a) Daily values of density of solar proton energy flux in 1–100 MeV range during 1994–2003 (based on GOES data). (b) Daily values of averaged energy of solar protons in 1–100 MeV range during 1994–2003 (based on GOES data).

activity that occurred during 1995–1996, then the beginning of its increase during 1997–1998, local minima in 1999, and the main maxima during 2000–2001. It is interesting to notice that after the beginning of negative slope in proton fluxes behavior in 2002, strong SPE occurred after 28th October 2003. This SPE had a similar intensity as the most pronounced SPE of 23rd cycle—Bastille Day event.

At the same time there are important changes that appear if we use another characteristic for solar proton flux—mean energy of single proton. Fig. 1(b) shows temporal variability of daily mean proton energy. Looking of this figure we can see that the greatest peak on it belongs to SPE of 4th November 2001. This event was also pronounced on Fig. 1(a) and had the “second place” after Bastille Day event (July 2000). Revealed changes between Figs. 1(a) and (b) presented above illustrate the difference between energy spectrums of each SPE. It should be mentioned that we supposed in our calculations the exponential form of energy spectrum for 1–10 MeV and 10–100 MeV. The characteristics of these exponents have been calculated.

Joint analysis of Figs. 1(a) and (b) permitted us to select the six most pronounced SPEs for last solar maxima: 14th July 2000 (Bastille Day event), 8th November 2000, 24th September 2001, 4th November 2001, 22nd November 2001, and 28th October 2003. Ionization rates caused by these selected SPEs for 70°N have been calculated for using in photochemical modeling to take into account additional source of  $\text{NO}_x$  and  $\text{HO}_x$  production.

### 3. Ionization of the atmosphere by SPEs during 2000–2003

As we know (Thomas, 1974), in the absence of SPEs the ionization of the atmosphere below 90 km is controlled by several sources:  $L\alpha$  (about 10 ion pairs/( $\text{cm}^3\text{s}$ ) at 90 km and smaller at lower altitudes); UV ionizing radiation (about 1 ion pairs/( $\text{cm}^3\text{s}$ ) at 90 km and smaller at lower altitudes); GCRs (about 0.1 ion pairs/( $\text{cm}^3\text{s}$ ) at 60 km and smaller at higher altitudes). Other sources are smaller than the sources mentioned above. At the same time, during strong SPEs the situation may be changed strongly (Solomon et al., 1983).

Ionization rates caused by solar protons at 70°N for selected SPEs during 2000–2003 have been calculated using the method described by Vitt and Jackman (1996). Proton fluxes taken from GOES database with high temporal resolution (5 min) and in integral energetic canals ( $>10$ ,  $>30$ ,  $>50$ ,  $>60$ ,  $>100$ ,  $>370$ ,  $>480$ , and  $>640$  MeV) have been used for the determination of the differential spectra. Temperature and pressure vertical profiles needed for calculations have been taken from

COSPAR International Reference Atmosphere (CIRA', 86). It was supposed by the authors that used latitude is always placed inside polar cap.

Figs. 2 and 3 show calculated ionization rates caused at 70°N by SPEs selected above. We see that the presented cross-section of ionization rates for the most pronounced SPEs has its own “portrait”, which determines, by a combination of several factor, intensity of solar proton fluxes, energetic spectrum, the length of proton fluxes penetrating in the polar atmosphere in time, and at last the parameters of the polar atmosphere (pressure and temperature) at the moment of SPE.

Fig. 2(a) shows cross-section (height–time) of ionization of the atmosphere caused by Bastille Day event at 70°N. We see that increased ionization rate occurred in the middle of 14th July 2000 with the maximum on 15th July, which was placed around 65–70 km, reaching the magnitude of  $2.7E+10$  (pairs of ions/( $\text{m}^3\text{s}$ )) or  $2.7E+4$  (pairs of ions/( $\text{cm}^3\text{s}$ )).

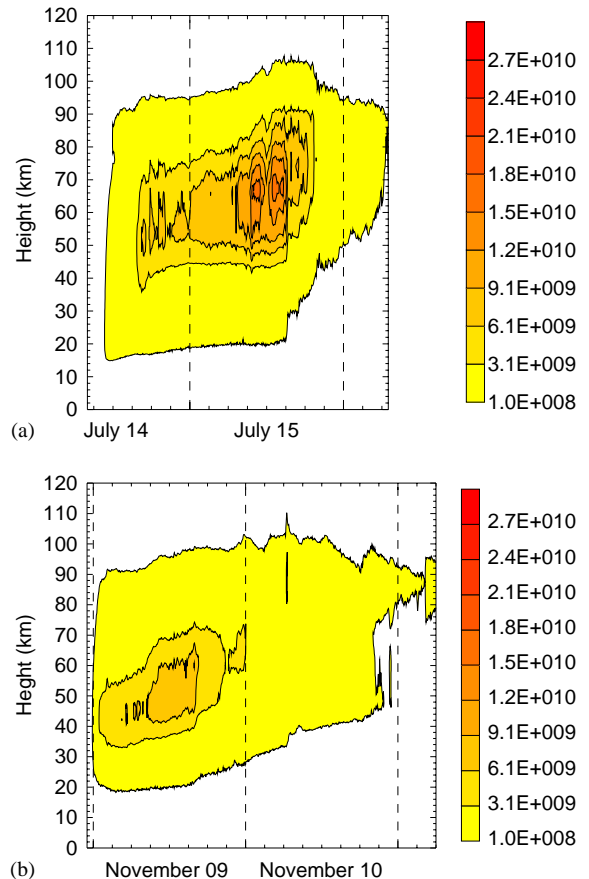


Fig. 2. Ionization rates (pairs of ions  $\times \text{m}^{-3}\text{s}^{-1}$ ) in the mid-polar atmosphere (70°N) caused by protons from solar flare at (a) 1024 UT of July 14, 2000 (calculations based on GOES data). (b) 2328 UT of November 08, 2000 (calculations based on GOES data).

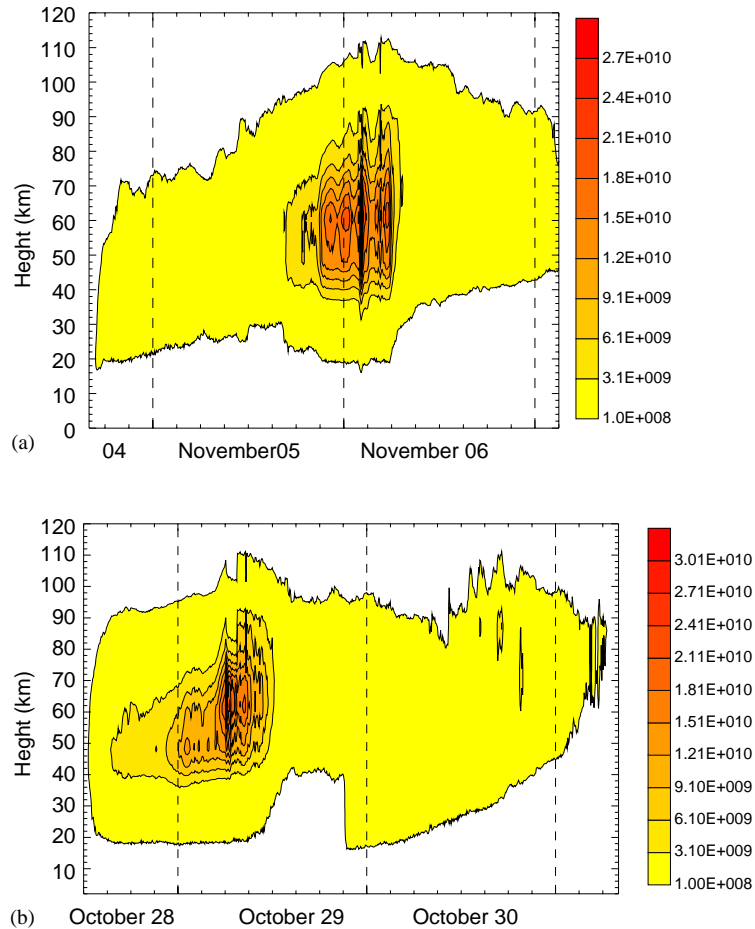


Fig. 3. Ionization rates (pairs of ions  $\times \text{m}^{-3}\text{s}^{-1}$ ) in mid-polar atmosphere ( $70^\circ\text{N}$ ) caused by protons from solar flare at (a) 1620 UT of November 04, 2001 (calculations based on GOES data). (b) 1110 UT of October 28, 2003 (calculations based on GOES data).

Fig. 2(b) shows cross-section (height–time) of ionization of the atmosphere caused by SPE of 8th November 2000 at  $70^\circ\text{N}$ . One can see that increased ionization occurred in the beginning of 9th November 2000 with its maximum during mid-day. Vertical localization of ionization rate was placed around 50 km (lower than during previous SPE) reaching the lower magnitude in its maxima  $8E+9$  (pairs of ions/( $\text{m}^3\text{s}$ )) or  $8.7E+3$  (pairs of ions/( $\text{cm}^3\text{s}$ )).

Fig. 3(a) shows cross-section of ionization caused by SPE of 4th November 2001 at  $70^\circ\text{N}$ . This figure looks similar to the previous figure (short interval of high ionization, which localized between 50–75 km). The magnitude of ionization rate in its maximum was not higher than  $2E+10$  (pairs of ions/( $\text{m}^3\text{s}$ )) or  $2E+4$  (pairs of ions/( $\text{cm}^3\text{s}$ )).

Finally, we will look at Fig. 3(b), which shows ionization rates caused by SPE that occurred on 28th October 2003 (practically two years later after “official”

solar maximum). We can see that this SPE was pronounced one day later, 29th October 2003, and had rather strong magnitude of ionization in its maxima ( $3E+10$  (pairs of ions/( $\text{m}^3\text{s}$ )) or  $3E+4$  (pairs of ions/( $\text{cm}^3\text{s}$ ))), compared to Bastille Day event, had similar height displacement (50–80 km), but had more shorter time of its prolongation.

So, summarizing the results presented above we may conclude that some of the most pronounced SPEs of the last solar maximum described above induced strong ionization rates in the middle atmosphere comparable to the Bastille Day event which occurred in July 2000. It is important to also underline that ionization rates caused by these SPEs were several orders of magnitude larger (the magnitudes were about  $1E+4$  (pairs of ions/( $\text{cm}^3\text{s}$ )) or more) than the usual background condition described in Section 3 of this paper.

As was mentioned above, each pair of ions produces additional nitrogen and hydrogen oxides in the

atmosphere and disturbs chemical composition of the atmosphere. We will present below the results of photochemical simulations, which show the response of ozonosphere to several of the most pronounced SPEs that occurred during the maximum of 23rd cycle of solar activity.

#### 4. Response of ozonosphere to SPEs during 2000–2003 (photochemical simulations)

##### 4.1. Model description

We will now begin with a short description of the photochemical model used for calculations of neutral species response to SPEs.

One-dimensional time-dependent numerical photochemical model was used to calculate the sensitivity of ozone content over polar regions to SPEs. 1D models are considered as a global averaged models in latitude and longitude, and vertical transfer is usually parameterized as an eddy diffusion, but authors believe that such a kind of models are also useful tools when we have good initial conditions and not very long numerical scenario (shorter than one month). It is also possible to include a certain effective velocity of vertical transfer ( $w$ ).

The behavior of minor gas components in the model used for calculations is described by the set of continuity equations for the number of components ( $i$ ) (Krivolutsky et al., 2001c):

$$\frac{\partial n_i}{\partial t} + \frac{\partial(n_i w)}{\partial z} - \frac{d}{dz} \left\{ K \left[ \frac{\partial n_i}{\partial z} + \left( \frac{1}{T} \frac{\partial T}{\partial z} + \frac{1}{H} \right) n_i \right] \right\} = P_i - L_i. \quad (1)$$

Here,  $P_i$  and  $L_i$  are the photochemical sources and losses of particles, respectively;  $n_i$  is the particle number density of the  $i$ th component,  $T$  is temperature,  $H$  is the scale height,  $K$  is the coefficient of vertical component of eddy diffusion and  $z$  is the height above the Earth's surface.

A technique of “chemical families” in accordance with Turco and Whitten (1974) was used for solving the aeronomical part of the basic equations of the model. It was shown (Garcia and Solomon, 1983) that “family” technique “works” well in the stratosphere, mesosphere, and lower thermosphere. Turbulent transport by eddy diffusion was included using usual numerical methods at each step of integration. The photochemical block of the model describes the interaction between 60 minor components participating in 164 chemical and photochemical reactions. The list of the model chemical gas phase and reactions of photodissociation are also presented in the paper published by Krivolutsky and Vyushkova (2002). Reaction rate constants, absorption

cross-sections, solar radiation intensity, and quantum outputs were assigned in the tabulated form according to published materials (Atkinson et al., 1989; DeMore et al., 1997). Used time-step of integration was 100 s and vertical resolution of the model was 2 km. Boundary conditions for all chemical species were fixed at lower boundary in accordance with observations. During calculations, we also assumed fixed concentrations of long-lived components as the upper boundary conditions of the integration region (0–100 km). In so doing, the concentrations of short-lived components were calculated from the conditions of photochemical equilibrium. The inclusion of tropospheric chemistry made it necessary to consider additional non-photochemical escapes for certain components (the so-called “washing out”). Vertical velocity ( $w$  in Eq. (1)) was assumed zero in all calculations.

The photochemical sources and escapes of chemical particles were calculated in the usual way

$$J_i(z) = \int \Phi_i(\lambda) I(\lambda, z) \sigma_i(\lambda, T) d\lambda, \quad (2)$$

where  $\Phi_i(\lambda)$  is quantum output of the process,  $\sigma_i(\lambda, T)$  is cross-section of radiation absorption, and  $I(\lambda)$  is solar radiation intensity at a  $z$  height as a function of wavelength  $\lambda$ :

$$I(\lambda, z) = I_\infty(\lambda) \exp \left( - \int \sum n_j(z) \sigma_j(\lambda, T) \sec \theta dz \right). \quad (3)$$

Here,  $I_\infty(\lambda)$  is the intensity of solar radiation at the atmospheric boundary and  $\theta$  is the zenith angle of the Sun. Current photolysis rates have been calculated for each hour (without daily averaging) during the integration of the model. In so doing, we also took into account the annual variation in the zenith angle of the Sun at the given latitude and its dependence on the height above the Earth's surface. Chapman functions have been used instead of  $\sec \theta$  in Eq. (3), when  $\theta \geq 75^\circ$ .

Special module was developed and introduced into the model to calculate simultaneously the additional production on  $\text{NO}_x$  and  $\text{HO}_x$  caused by ionization during each SPE. It was assumed in simulations that each pair of ions generated by solar protons in the atmosphere produced 1.27 molecules of NO and 2.0 molecules of OH in accordance with the papers listed above.

Fig. 4 shows calculated vertical structure of ozone, atomic oxygen, and  $\text{HO}_x$  compounds and separately for day (daily averaged values) and night conditions at  $40^\circ\text{N}$ . One can see that the photochemical model reproduces vertical structure of these species and its daily variations well (increased ozone during the night, and increased  $\text{HO}_x$  and atomic oxygen in the presence of sunlight). Equal values at upper boundary of atomic oxygen concentrations (non-excited) for night and day conditions, which we see in this figure, were caused by fixed boundary conditions used in the model for  $\text{O}_x$ .



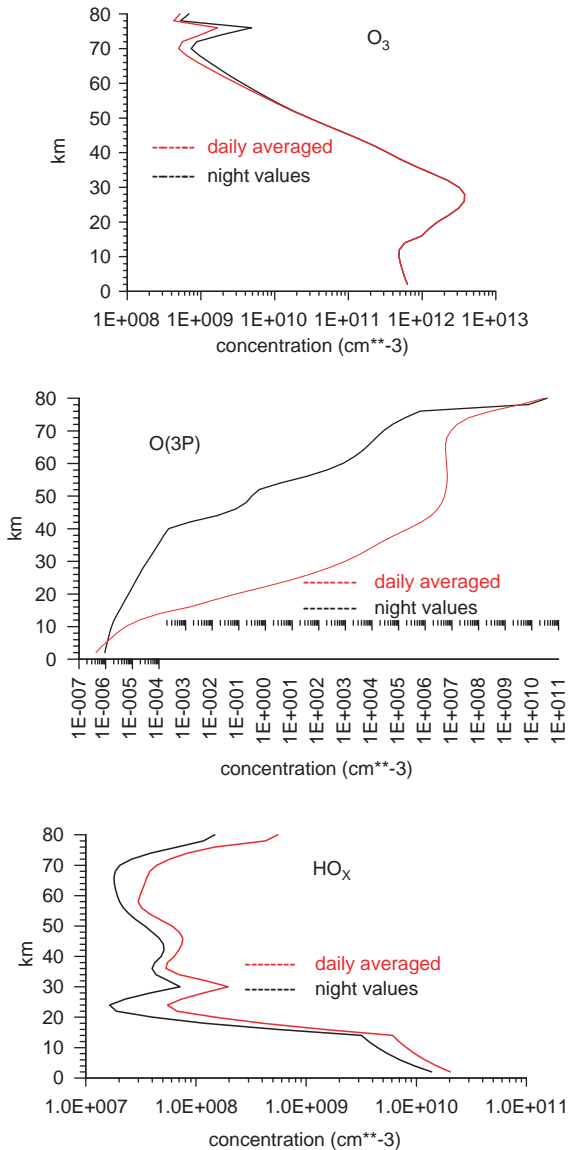


Fig. 4. Vertical profiles of ozone, atomic oxygen, and HO<sub>x</sub> for day (red line) and night (black line) conditions at 40°N as was simulated in the photochemical model.

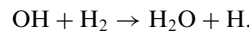
We present below some results of photochemical simulations, which demonstrate the response of chemical composition to SPEs selected above.

#### 4.2. Results of simulations

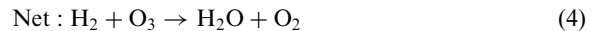
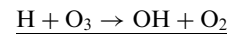
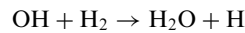
We begin with the famous SPE of last solar maximum—Bastille Day event (July 2000). Fig. 5(a) shows the calculated ozone response (%) after this event. One can see that the ozone was strongly (about

60–70%) destroyed in the mesosphere after this SPE. Such depletion is very similar to observations, as was shown before (Jackman et al., 2000; Krivolutsky, 2001a), and is the result of increased HO<sub>x</sub> and NO<sub>x</sub> production. The amount of these “families” were increased by several times after this event, as was shown in the papers mentioned above. At the same time, as was shown by Jackman et al. (2001), calculated increased amount of NO<sub>x</sub> was larger than UARS data shown (measurements of HALOE instrument). So, it seems that the similarity between the ozone changes resulting from photochemical simulations and observed from space was mostly caused by HO<sub>x</sub>-induced catalytic destruction.

We can add to the previous results obtained by groups mentioned, which calculated ozone response after SPE of July 2000, the results of water vapor response. We understand (see Section 1 of this paper) that the source of OH production caused by ionization is the existence of water vapor and its clusters in the stratosphere and mesosphere. At the same time additional OH amount leads to H<sub>2</sub>O production in the reaction (included in the model)



Then this reaction together with reaction  $\text{H} + \text{O}_3 \rightarrow \text{OH} + \text{O}_2$  forms the following catalytic cycle:



So, focusing on the chemical reaction list written above, it is possible that water vapor molecular can be increased due to the coronal mass ejections. Fig. 7(a) shows the results of calculations, which demonstrate such increase (weak). The magnitude of this effect is not greater than 2%, but has a very long “tail”. It should be mentioned that other catalytic cycles also exist (Brasseur and Solomon, 1984), but it seems that cycle (4) is the most important one for this case.

Figs. 5(b) and 6(a), (b) also show the calculated ozone response during and after SPEs of 8th November 2000; 4th November 2001; and October 28 2003, respectively. The results show that calculated responses of SPEs 8th November 2000 and of 4th November 2001 were also very pronounced and strongly destroyed the ozone in the higher stratosphere and in mesosphere at 70°N in accordance with photochemical simulations. Two others SPEs of this solar maximum were pronounced weaker in ozone as was found by calculations.

We now present our results, which demonstrate the response of chemical composition of the middle atmosphere at 70°N caused by CME of October 2003.

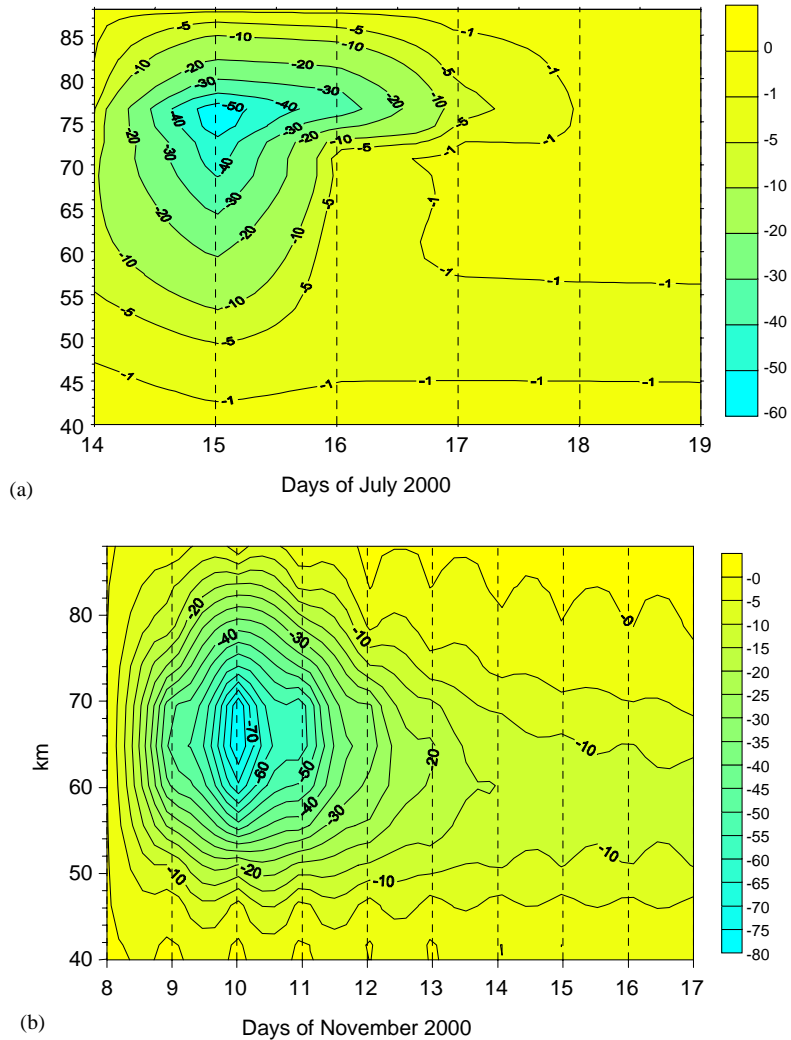


Fig. 5. Ozone depletion (%) over the periods (a) July 14–19, 2000; (b) November 8–13, 2000 at 70°N, caused by the coronal mass ejection (CME) of July 14, 2000 (photochemical simulations).

#### 4.2.1. Solar proton event of October 2003

Returning to Fig. 3(b), which shows the ionization rates in mid-atmosphere caused by CME of October 2003, we see that the start of increase in ionization rates began in the second half of 28th October. At the same time, as we see in Fig. 3(b), ionizations rates with magnitudes more than  $1.E+10$  (pairs of ions/( $m^3 s$ )) occurred in 29th of October with its maximum ( $3.E+10$ ) around by mid-day. It should be noticed that extreme ionization rates were near the maximum of ionization after Bastille Day event, but it did not last long (see Figs. 2(a) and 3(b) for comparison). So, we see that external forcing on the atmosphere by this SPE important for chemical composition lasted not more than half a day. We now go to calculated results of chemical species response during and after the event of October 2003.

*OH*: Additional  $HO_x$  response caused by SPE leads to intensification of chemical catalytic cycle in the atmosphere (Brasseur and Solomon, 1984):

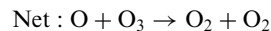
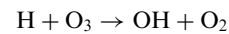
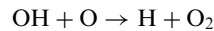


Fig. 7(a) shows corresponding response (%) in OH content caused by CME. We can see that the amount of OH was approximately increased twice on the first day after SPE (not shown in the figure), with the maximum of the effect after two days. One can also see that this maxima belongs to night conditions and it is the consequences of strong daily variations of this species. At the same time, the effect of SPE in OH lasted several days later, with the conservation of the reduced and the



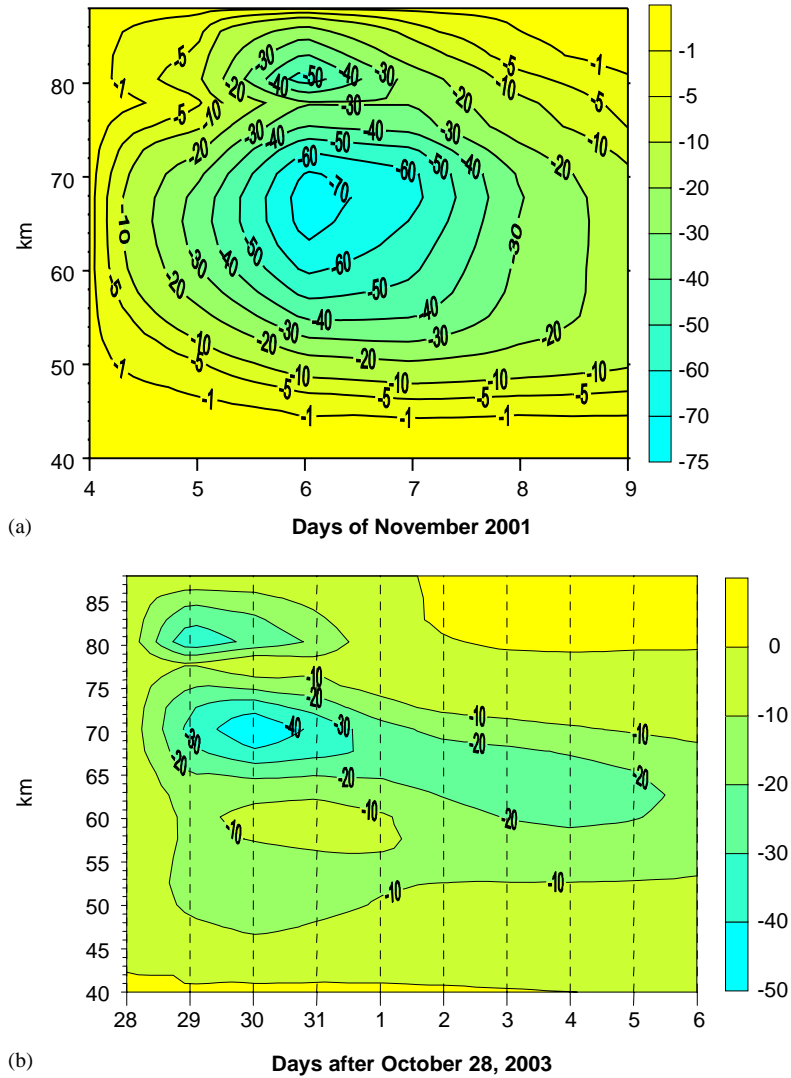


Fig. 6. Ozone response (%) caused by the coronal mass ejection (CME) of (a) November 4, 2001; (b) 28 October 2003 as simulated by photochemical model.

increased amount (about 50%) during several (ten in the figure) days. We discuss below the existence of such “tail” in OH response.

*NO*: The increasing of this minor species also leads to the intensification of another chemical catalytic cycle, which is as follows (Brasseur and Solomon, 1984):

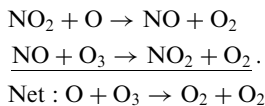


Fig. 7(b) shows the results of computations. One can see that this long-lived species was doubly increased after several days after CME and had long “tail” (full

length is not shown in the figure). Some visible slope in the displacement of the maximum possibly depends on the intensity of the process of turbulent diffusion in vertical direction.

*O<sub>3</sub>*: We now look on the structure of the ozone response after SPE. These changes in ozone content, which are illustrated below, were induced by corresponding changes in *NO<sub>x</sub>* and *HO<sub>x</sub>* presented above in Fig. 7(a) and (b). However, we must remember that the interaction between ozone and species mentioned has non-linear character.

We now return to Fig. 6(b), which shows calculated changes in the ozone. Numerical scenario lasted approximately two weeks after CME. We can see that changes

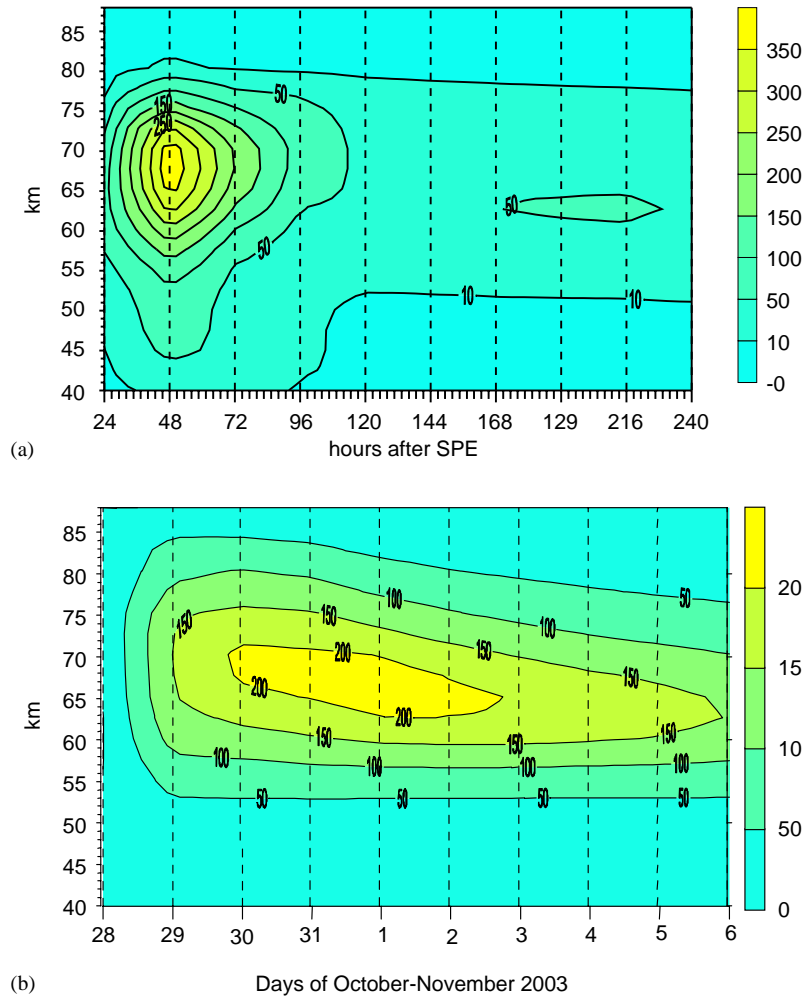


Fig. 7. (a) OH and (b) NO increase (%) caused by the coronal mass ejection (CME) 28 October 2003 as simulated by photochemical model.

(depletion) in ozone exist between 40 and 90 km. The magnitudes of these changes differ strongly with time and altitude. Then we can find two local maxima in this figure: one is around 80 km, and the second is in the range of altitudes of 65–70 km and with 3–4 days delay. It also seems that both maxima were induced by  $\text{HO}_x$  “working”, but their appearance depends on the first portion of solar proton with lower energy, and the second portion of solar protons with higher energy. The “tail” of ozone response, which we see in Fig. 6(b) and which lasted for more than 10 days, was caused by  $\text{NO}_x$  forcing. Maximum of ozone depletion (calculated) after CME in October 2003 is about 50% and occurred after 3 days around 70 km level. So, the effect (in %) in ozone was smaller in comparison to Bastille Day event (July 2000) and 4th November 2001.

$\text{H}_2\text{O}$ : Fig. 8(b) shows weak positive response (about 2% and smaller) in  $\text{H}_2\text{O}$  content caused by SPE. We can

see that the magnitude of OH increase after SPE in October 2003 was similar to the effect of SPE in July 2000, with the maximum of the effect four days later, and placed near the 75 km level (the same that for the maximum in OH response). We can also see that this maxima belongs to night conditions the long-term “tail” in the response of water vapor content. So, we suppose that similar “tail” in OH response (see Fig. 7(a)) was induced by photodissociation of additional amount of  $\text{H}_2\text{O}$ .

## 5. Concluding remarks

Summarizing the results of computations of ionization rates and the response of chemical compounds in the middle atmosphere after the most pronounced CMEs of 23rd solar maximum, we write the list of the

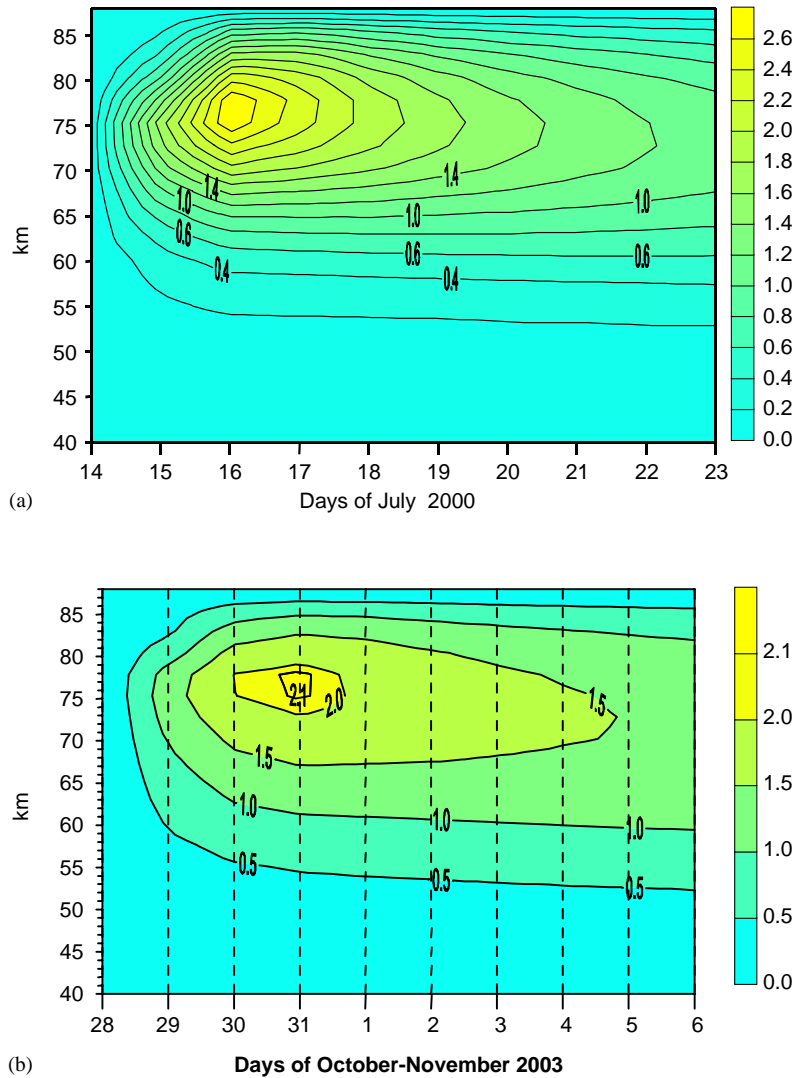


Fig. 8. Water vapor increase (%) of (a) July 14, 2000 and (b) October 28, 2003 at 70°N (photochemical simulations).

most pronounced CMEs in ozonosphere of the Earth, which occurred on

- 14th July 2000 (ozone depletion about –60% in the mesosphere);
- 8th November 2000 (ozone depletion about –70% in the mesosphere);
- 4th November 2001 (ozone depletion about –70% in the mesosphere);
- 29th October 2003 (ozone depletion about –50% in the mesosphere).

Such ozone depletion in model runs was caused by catalytic cycles with OH and NO, which were born due to ionization of the atmosphere by solar energetic protons.

Each of above listed SPEs caused comparable ionization rates in the atmosphere of the Earth (in its maxima), but had different energetic spectrum and length of increased ionization area in time. In spite of the fact (obtained by the measurements from the instruments of GOES satellites) that the most intensive proton fluxes were registered during and after SPE of October 2000, another three SPEs had similar calculated response in atmospheric composition and it needs special studies to find their response in observations.

We should also make short comments concerning the response of the short-lived species (ozone and OH) in the mesosphere during and after SPEs. As we know these compounds have rather strong daily variability from day to night (see Fig. 4), but we did not see this effect presented is Figs. 4(a), (b), and 5(a), (b). We must

underline that these figures present the difference between two scenarios: with and without SPEs, both which contain daily variations. So, the effect of day–night variations was mostly removed from presented results. The second moment in relation to this point is the rather short interval of strong ozone response. So, the amplitude of daily variations was not much disturbed during 10 days to show daily effects on the figures.

With respect to results presented with weak increase of water vapor content caused by CME in mid-atmosphere (Fig. 8(a), (b)), the authors believe that it is a preliminary result and it needs additional modeling using ions-neutral photochemical models. At the same time, we must remember that positive trends in water vapor in the lower and middle atmosphere exist in accordance with observations and the source of these trends is still under discussion (SPARC, 2000).

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